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Abstract

Accurate assessments of the charm and bottom cross sections and kinematic distributions in hadron-hadron collisions are needed in order to understand the behavior of heavy flavors in more complex collisions. Neither the charm nor bottom cross sections were measured at $\sqrt{S} = 200$ GeV before the startup of the Relativistic Heavy Ion Collider (RHIC). The RHIC detectors are capable of measuring the heavy flavor transverse momentum distributions to $p_T \sim 0$, making estimates of the total heavy flavor cross section feasible at a collider. It is thus possible to obtain and compare the total heavy flavor cross sections at RHIC with those measured at other energies. The charm production data, in particular, can have a considerable spread in the measured cross sections, even at a single energy. In addition, the small charm mass can lead to large theoretical uncertainties. We assess the theoretical uncertainties on the heavy flavor (charm and bottom) hadroproduction cross section. We discuss the importance of the quark mass, the renormalization and factorization scales and the parton densities on the estimate of the uncertainty.

Key words: heavy flavor, higher-order calculations
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1. Introduction

Accurate heavy flavor measurements are important for determining the angles in the unitarity triangle, asymmetries for CP violation studies and heavy flavor hadron branching ratios for rare decays. However, these measurements often involve studies of relative rates and do not typically require high-statistics measurements of the total heavy flavor production cross section. In more complex collisions, such as proton-proton (pp),

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deuteron-gold (d+Au) and gold-gold (Au+Au) collisions at the Relativistic Heavy-Ion Collider (RHIC), while the relative rates are still important, the absolute rates are also needed to understand certain probes, as we discuss below.

Obtaining the absolute cross section is a nontrivial task, involving some model assumptions. Heavy flavor production is most straightforward to fully reconstruct via decays to two-body charged-particle final states. For example, neutral D mesons (BR($D^0 \to K^-\pi^+) = 3.8\%$) and, by extension, the excited states $D^{\star +}$ and $D^{\star 0}$ which both decay to D^0, are most likely to be reported. These partial rates need to be converted to the full charm hadron production rate by correcting for the decay branching ratio. However, the measured charm mesons represent only a fraction of all charm hadrons. The D meson ($D^0 + D^+$) cross section thus needs to be multiplied by a correction factor to account for the unmeasured charm hadrons [1], a factor of 1.2-1.5. The single inclusive rate is converted to the pair rate by dividing by two. In addition, most experiments do not cover full phase space. Extrapolation from the detector acceptance to full phase space is required. While the total cross sections can be calculated perturbatively due to the finite quark mass, the extrapolation is generally be done through simulations, either with leading (*e.g.* PYTHIA [2]) or next-to-leading (MC@NLO [3], HVQMNR [4]) order matrix elements. Finally, experimental analyses of the total cross section requires knowing the collider luminosity over the course of the run.

This proceedure works very well for top production. The uncertainties due to the scale choice, parton densities and kinematics choice are on the order of 10% for a given top quark mass while the ratio of the approximate NNLO relative to the exact NLO result is less than 1.1, showing that further higher-order corrections are small [5,6].

Unfortunately this is not the case for the lighter 'heavy' flavors, charm and bottom. In particular, the reported charm cross sections at a single center-of-mass energy can differ by an order of magnitude between experiments with different detector acceptances. This spread can be attributed to poor statistics; changes in decay branching ratios with time; the assumed A dependence (A vs. $A^{2/3}$); and extrapolations to full phase space made before perturbative QCD calculations were available. Early values were obtained by assuming a power law for the x_F distribution, $(1 - x_F)^c$ where $x_F = p_z/(\sqrt{S}/2) = 2m_T \sinh y/\sqrt{S}$. The parameter c was either fit to data over a finite x_F range or simply assumed. Such parameterizations could lead to large overestimates of the total cross section for $0 < c < 2$, especially when data were taken only near $x_F = 0$. Lepton measurements with beam dumps were more conservative but were typically at more forward x_F. A UC Davis student is re-evaluating all the previous data using state-of-the art calculations of the kinematic distributions.

2. Heavy Flavor Measurements at RHIC

In high-multiplicity environments, such as those at RHIC, distinguishing two and three body decays of D mesons from the combinatorial light hadron background is extremely difficult. The most accurate analyses of reconstructed D mesons at RHIC are therefore in pp and d+Au collisions [7,8]. Heavy flavor cross sections have also been reported using 'non-photonic' electron spectra [7,9,10] where a hadronic cocktail is used to remove contributions to the electron spectra that do not arise from semileptonic heavy flavor decays. Unfortunately, inclusive lepton spectra alone cannot reveal whether the measured leptons originate from charm or bottom hadron decays. Modeling and additional analysis tools are needed. It is also desirable to compare the RHIC data at $\sqrt{S_{NN}} = 200$ GeV with measurements at other energies to check whether the RHIC data are consistent both with previous measurements and with theoretical predictions.

While the measurements are difficult, total charm cross sections have been reported at RHIC. The STAR values are somewhat higher than those reported by PHENIX. The cross sections differ by about 1.5 times the combined standard deviations of the two measurements, obtained by adding the statistical and systematic uncertainties in quadrature [11]. These early results have yet to be reconciled. Hopefully more data, combined with detector upgrades and improved analyses, will make it possible to bring the results from the two experiments into agreement.

Heavy-flavor probes of heavy-ion collisions shed light on the conditions of the system at early times. For example, in gluon-rich environments, quarks traversing the medium are expected to lose energy. Larger mass charm and bottom quarks are expected to lose less energy than light quarks in collisions with light partons. Indeed, bottom quarks are expected to lose even less energy than charm quarks [12]. However, the ratio of the heavy flavor semileptonic decay rate in AA relative to pp interactions (both measured in the same setup) is consistent with that for light flavors, suggesting that light and heavy flavor energy loss is the same, an unexpected result [9,13]. At high transverse momentum, $p_T \gg m_c$, the charm quark mass may be neglected so that charm and light quark energy loss could be similar at sufficiently high p_T. However, bottom decays to electrons contribute about 50% of the inclusive electron spectra at $p_T \sim 4 - 6$ GeV/c [14,15], a range where m_b is not negligible. We note that while STAR and PHENIX do not agree on the total charm rate at RHIC, their measurements of the relative heavy and light quark energy loss and radial flow of heavy quarks are in agreement, as well as their estimate of the bottom contribution to the inclusive electron yield as a function of p_T [11].

The total charm yield is also needed to normalize the J/ψ rate in heavy-ion collisions where the initial J/ψ yield is expected to be considerably suppressed [16]. At $\sqrt{S_{NN}} =$ 200 GeV, the charm cross section is large enough for multiple $c\overline{c}$ pair production in a single head-on Au+Au collision. If these uncorrelated c and $\overline{c}$ quarks are sufficiently close in phase space, they may coalesce to produce a final-state J/ψ, reducing the apparent J/ψ suppression. These secondary J/ψ's will have softer p_T and narrower rapidity distributions [17].

3. Separating Charm From Bottom

While detector upgrades should allow better separation of c from b through direct reconstruction of c and b hadrons or displaced vertex measurements, interpreting the present heavy-flavor data from high-energy heavy-ion collisions requires separation of c and b decays to leptons. Exclusive measurements of signals involving both the Q and $\overline{Q}$ decay products such as opposite-sign lepton pairs and lepton-hadron correlations may provide more information than measurements of inclusive spectra alone. Since lepton pairs such as e^+e^- signal spectra and $e\mu$ pairs contain a mixture of $c\overline{c}$ and $b\overline{b}$ decays [18], lepton-hadron correlations are perhaps a more useful tool for charm/bottom separation.

An interesting azimuthal correlation method has recently been proposed by Mischke

[19]. It makes use of the fact that both c and b quarks produce final-state D^0 mesons about 60% of the time: $\mathrm{BR}(c \to D^0 X) = 56.5 \pm 3.2\%$ while $\mathrm{BR}(b \to B \to D^0 X) = 59.6 \pm 2.9\%$. The product D^0 can be reconstructed via $D^0 \to K^-\pi^+$ (likewise $\overline{D}^0 \to K^+\pi^-$). Semileptonic decays of the heavy flavor hadrons thus allow c/b separation via eK correlations.

Charm pair decays predominantly result in like-sign eK pairs by triggering on a lepton from $\overline{c} \to \overline{D}^0 \to K^+ e^- \overline{\nu}_e$ opposite a kaon from the $c \to D^0 \to K^-\pi^+$ decay. In this case, the e^- and K^- are back-to-back ($\Delta\phi = \pi$, away side).

On the other hand, $b\overline{b}$ decays result in both like- and opposite-sign eK pairs. For example, suppose a B^+B^- pair is produced. The B^- can decay semileptonically to $D^0 e^- \overline{\nu}_e$. The D^0 then decays via $K^-\pi^+$, making a like-sign e^-K^- pair on the same (near) side with $\Delta\phi = 0$. Thus like-sign eK pairs on the near side originate $b\overline{b}$ decays while those on the away side originate from $c\overline{c}$ pairs. In addition, the B^+ opposite the B^- can decay to $\overline{D}^0$ which subsequently decays to $K^+\pi^-$, giving an opposite sign e^-K^+ pair on the away side. Such separation techniques are necessary to distinguish between physics effects on c and b quarks in heavy-ion collisions.

4. Determining Theoretical Uncertainties

We now discuss the theoretical uncertainties in the total heavy flavor cross section. While the consistency of the data are important, there is also more than one way to calculate the total cross section using higher-order techniques. These two methods should, aside from unconstrained higher-order effects, be equivalent. If the total hadronic cross section is calculated using the NLO matrix elements, we have [21]

$$\sigma_{pp}(S, m^2) = \sum_{i,j=q,\overline{q},g} \int dx_1\, dx_2\, f_i^p(x_1, \mu_F^2)\, f_j^p(x_2, \mu_F^2)\, \widehat{\sigma}_{ij}(s, m^2, \mu_F^2, \mu_R^2) \quad (1)$$

where x_1 and x_2 are the parton momentum fractions; μ_F and μ_R are the factorization and renormalization scales; and f_i^p are the proton parton densities. The produced heavy quark is not an active flavor so that α_s is calculated with $n_{\mathrm{lf}} = 3, 4$ for c and b respectively. Here the mass is the only relevant energy scale.

However, when kinematic distributions are measured, especially at $p_T \gg m$, the state-of-the-art calculation is the fixed-order next-to-leading logarithm approach (FONLL). FONLL treats the heavy quark as an active light flavor at $p_T \gg m$. Thus the number of light flavors used to calculate α_s includes the heavy quark, *i.e.* 4 for charm and 5 for bottom. The same number of flavors, $n_{\mathrm{lf}} + 1$, is also used in the fixed-order component of the FONLL calculation.

The calculation of the inclusive electron spectrum involves three components: the p_T and rapidity distributions of the heavy quark Q, calculated in perturbative QCD; fragmentation of the heavy quarks into heavy hadrons, H_Q, described by phenomenological input extracted from e^+e^- data; and the decay of H_Q into electrons according to spectra available from other measurements,

$$\frac{E d^3\sigma(e)}{dp^3} = \frac{E_Q d^3\sigma(Q)}{dp_Q^3} \otimes D(Q \to H_Q) \otimes f(H_Q \to e)\ . \quad (2)$$

The electron decay spectrum, $f(H_Q \to e)$, includes the semileptonic branching ratios.

The total cross sections obtained by integrating the FONLL kinematic distributions, Eq. (2), should be equivalent to that obtained by convoluting the total partonic cross sections with parton densities, Eq. (1). The perturbative parameters are the heavy quark mass and the value of the strong coupling, α_s, while the parton densities are a nonperturbative input. We take $m_c = 1.5$ GeV and $m_b = 4.75$ GeV as the central values and let $1.3 \leq m_c \leq 1.7$ GeV and $4.5 \leq m_b \leq 5$ GeV. The sensitivity of the cross section to variation of μ_F and μ_R is an estimate of the perturbative uncertainty due to the absence of higher orders. Since Eq. (1) is independent of the kinematics, we take $\mu_{R,F} = \mu_0 = m$ as the central value and varied the two scales independently within a 'fiducial' region defined by $\mu_{R,F} = \xi_{R,F}\mu_0$ with $0.5 \leq \xi_{R,F} \leq 2$ and $0.5 \leq \xi_R/\xi_F \leq 2$. The following seven sets are used: $\{(\xi_R, \xi_F)\} = \{$(1,1), (2,2), (0.5,0.5), (1,0.5), (2,1), (0.5,1), (1,2)$\}$. The uncertainties from the mass and scale variations are added in quadrature. The envelope containing the resulting curves,

$$\sigma_{\rm M} = \sigma_{\rm c} + \sqrt{(\sigma_{\mu,{\rm M}} - \sigma_{\rm c})^2 + (\sigma_{m,{\rm M}} - \sigma_{\rm c})^2}\ , \tag{3}$$

$$\sigma_{\rm m} = \sigma_{\rm c} - \sqrt{(\sigma_{\mu,{\rm m}} - \sigma_{\rm c})^2 + (\sigma_{m,{\rm m}} - \sigma_{\rm c})^2}\ , \tag{4}$$

defines the uncertainty. Here $\sigma_{\rm c}$ is the cross section calculated at the central value, $(\xi_R, \xi_F) = (1, 1)$ while $\sigma_{i,{\rm M}}$ and $\sigma_{i,{\rm m}}$ are the maximum and minimum values of the cross section for a given mass ($i = m$) or (ξ_R, ξ_F) set in the fiducial region ($i = \mu$). Although Eqs. (3) and (4) have been written for the total cross section, the corresponding limits of the inclusive distributions are similar but now $\mu_0 = m_T$ [20].

The energy dependence of the total $Q\overline{Q}$ cross section with CTEQ6M is shown on the left-hand side of Fig. 4. The charm uncertainty band broadens as the energy increases. The lower edge of the charm band grows more slowly with $\sqrt{S}$ above RHIC energies. The upper edge is compatible with the reported total cross sections at RHIC. When a set with a smaller α_s and a lower initial scale is used, the band narrows. The $b\overline{b}$ band is narrower and does not broaden with $\sqrt{S}$. The electron uncertainty bands at $\sqrt{S} = 200$ GeV are shown on the right-hand side. The PHENIX data [10] are in good agreement with the upper limit of the FONLL calculation while the STAR data [7,9] lies above it.

The calculated total charm cross section at $\sqrt{S} = 200$ GeV is 301^{+1000}_{-210} μb (NLO, $n_{\rm lf} = 3$) [21] and 256^{+400}_{-146} μb (FONLL, $n_{\rm lf} + 1 = 4$) [20] respectively. Since the NLO calculation uses three light flavors for charm, α_s changes more with μ_R than FONLL with one additional light flavor. The μ_F dependence of the charm cross section is large because $\mu_F \leq m_c$ is close to or below the minimum scale of the parton densities. If the FONLL calculation is made with three light flavors, the results are identical [21]. Because $m_b > m_c$, α_s is smaller for bottom production and the scale dependence of the cross section is considerably reduced, see the left-hand side of Fig. 4, and the difference between the NLO and FONLL bottom uncertainties is smaller.

Improved measurements at RHIC may reconcile the reported results, providing a better experimental baseline for heavy flavor probes of heavy-ion collisions. However, the absolute uncertainty on the $c\overline{c}$ cross section will remain large without significant improvements of the gluon parton densities at low x and low scale.

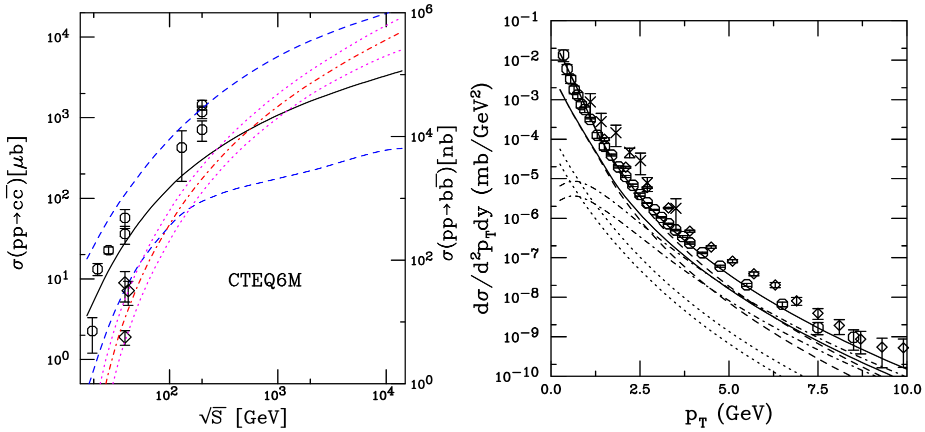

Fig. 1. Left-hand side: The NLO total $Q\overline{Q}$ cross sections as a function of $\sqrt{S}$, calculated with the CTEQ6M parton densities, compared to a subset of the $c\overline{c}$ and $b\overline{b}$ data. The solid and dot-dashed curves are the central results; the upper and lower dashed and dotted curves are the upper and lower edges of the charm and bottom uncertainty bands respectively. Right-hand side: Inclusive heavy flavor lepton spectra, calculated with FONLL, compared to the $\sqrt{S} = 200$ GeV PHENIX [10] and STAR [7,9] pp data.

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